

REMARKS

Claims 2, 5, 7 through 9, 13 and 15 of the substitute specification are canceled without prejudice while Claims 1, 3, 4, 6, 10 through 12 and 14 are amended to conform to like changes made to the claims of International application PCT/EP2004/013447 under Article 19 PCT on May 4, 2005 in response to the PCT Written Opinion dated March 4, 2005. Changes made to the substitute specification herein correspond to those filed in a response dated October 24, 2005 to the Written Opinion.

No new matter is added by the changes made herein.

Respectfully submitted,



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Title: METHOD FOR QUADRATURE-BIAS COMPENSATION IN
A CORIOLIS GYRO, AS WELL AS A CORIOLIS GYRO
WHICH IS SUITABLE FOR THIS PURPOSE

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BACKGROUND

Field of the Invention:

10 The present invention relates to Coriolis
gyroscopes. More particularly, the invention pertains
to a method for quadrature-bias compensation in a
Coriolis gyro, and to a Coriolis gyro which is suitable
for such ~~this~~ purpose.

Description of the Prior Art

15 Coriolis gyros (also referred to as
"vibration gyros") are ~~being~~ increasingly employed ~~used~~
for navigation. ~~purposes; they have~~ Such devices
include a mass system that ~~which~~ is caused to
oscillate. ~~The Each~~ mass system generally has a large
20 number of oscillation modes, ~~which are~~ initially
independent of one another. ~~In order~~ A specific
oscillation mode of the mass system is artificially
excited to operate the Coriolis gyro. ~~and this~~ Such
mode is referred to in the following text as the
25 "excitation oscillation".

Coriolis forces occur that ~~which~~ draw energy
from the excitation oscillation of the mass system When
the Coriolis gyro is rotated and ~~thus~~ transmit a

further oscillation mode of the mass system ~~which is~~
(referred to below ~~in the following text~~ as the "read
oscillation"). ~~In order~~ The read oscillation is tapped
off to determine rotations of the Coriolis gyro and a
5 corresponding read signal is investigated to determine
whether any changes have occurred in the amplitude of
the read oscillation which represent a measure of ~~the~~
rotation of the Coriolis gyro.

Coriolis gyros may comprise either ~~be in the~~
10 ~~form of both~~ an open-loop or ~~system and~~ a closed-loop
system. In a closed-loop system, the amplitude of the
read oscillation is continuously reset to a fixed
value (preferably zero) via respective control loops,
and the resetting forces ~~are~~ measured.

15 The mass system of the Coriolis gyro ~~which is~~
~~also~~ (referred to below ~~in the following text~~ as the
"resonator") may ~~in this case~~ be of ~~designed in~~ widely
differing designs. ~~ways~~. For example, it is possible to
use an integral mass system. Alternatively, it is
20 possible to split the mass system into separate two
oscillators ~~which are~~ coupled to one another via a
spring system and capable of ~~can carry out~~ relative
movements relative ~~with respect~~ to one another. For
example, it is known to use ~~for~~ a coupled system
25 comprising two linear oscillators ~~to be used, and this~~
~~is~~ (also referred to as a "linear double-oscillator"
system). ~~If~~ When such a coupled system ~~such as this~~ is

used, ~~then~~ alignment errors of the two oscillators with respect to one another are unavoidable due to ~~because~~ of manufacturing tolerances. The alignment errors of ~~the two oscillators with respect to one another~~ produce a zero error component in the measured rotation rate signal, the so-called "quadrature bias" (more precisely, ~~or to be more precise:~~ a quadrature-bias component).

SUMMARY AND OBJECTS OF THE INVENTION

It is therefore an ~~The of object on~~ which the invention ~~is based is~~ to provide ~~specify~~ a method and a Coriolis gyro for compensating ~~by means of which~~ ~~it is possible to compensate~~ for a quadrature-bias component as described above, ~~such as this.~~

The present invention addresses the preceding and other objects by providing, in a first aspect, a method for quadrature-bias compensation in a Coriolis gyro whose resonator is in the form of a coupled system comprising a first and a second oscillator. Such method includes determination of the quadrature bias of the gyro and production of an electrostatic field to vary the mutual alignment of the two oscillators with respect to one another. The alignment/strength of the electrostatic field is regulated so that the determined quadrature bias is as small as possible.

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In a second aspect, the invention provides
a Coriolis gyro in the form of a coupled system
comprising a first and a second linear oscillator.
Such gyro includes a device for production of an
5 electrostatic field for varying the alignment of the
two oscillators with respect to one another.

A device is provided for determination of
any quadrature bias of the Coriolis gyro as well as a
control loop for regulating the strength of the
10 electrostatic field as a function of the determined
quadrature bias so that the determined quadrature bias
is as small as possible.

In a third aspect, the invention provides a
Coriolis gyro having a first and a second resonator.
15 The resonators are each in the form of a coupled system
including a first and a second linear oscillator.

The first resonator is
mechanically/electrostatically connected/coupled to the
second resonator so that the two resonators can be
20 caused to oscillate in antiphase with respect to one
another along a common oscillation axis.

The foregoing and other features of the
invention will become further apparent from the
detailed description that follows. Such description is
25 accompanied by a set of drawing figures. Numerals of

the drawings, corresponding to those of the written description, point to the features of the invention with like numerals referring to like features throughout.

5 ~~According to the invention, this object is achieved by a method for quadrature bias compensation for a resonator having two linear oscillators as claimed in patent claim 1. The invention also provides an embodiment of a Coriolis gyro which is suitable for~~
10 ~~this purpose, as claimed in patent claim 6. A further suitable embodiment of a Coriolis gyro is contained in patent claim 12. Advantageous refinements and developments of the idea of the invention can be found in the respective dependent claims.~~

15 BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic illustration of ~~shows~~ one possible embodiment of a mass system having ~~which comprises~~ two linear oscillators, with corresponding control loops, for exciting ~~which are used to excite~~
20 the first oscillator.

Figure 2 is a schematic illustration of a ~~shows one~~ possible embodiment of a mass system having ~~which comprises~~ two linear oscillators with corresponding measurement and control loops for a
25 rotation rate Ω and a quadrature bias B_0 , as well as auxiliary control loops for compensation of the

quadrature bias B_0 .

Figure 3 is a schematic illustration ~~shows an~~
~~outline sketch~~ of a mass system in accordance with an
embodiment of ~~according to~~ the invention, which
5 comprises four linear oscillators, with corresponding
measurement and control loops for a rotation rate Ω and
a quadrature bias B_0 , as well as ~~the~~ auxiliary control
loops for compensation of the quadrature bias.

Figure 4 is a block diagram of an embodiment
10 of a ~~shows one preferred embodiment of the~~ control
system for incorporation into a mass system in
accordance with that illustrated in Figure 3 above.
~~shown in Figure 3.~~

15 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The method of ~~according to~~ the invention
for quadrature-bias compensation can be applied, in
particular, to Coriolis gyros whose resonators are in
the form of coupled systems comprising at least one
20 first and one second linear oscillator. ~~and has the~~
~~following steps: determination of the quadrature bias~~
~~of the oscillator system, production of an~~
~~electrostatic field in order to vary the mutual~~
~~alignment of the two oscillators with respect to one~~
25 ~~another, with the alignment/strength of the~~
~~electrostatic field being regulated such that the~~
~~determined quadrature bias is as small as possible.~~

The total quadrature bias of the oscillator system is preferably determined ~~in this case. This is preferably done~~ by demodulation of a read signal ~~which is~~ produced by ~~means of~~ read electrodes, with 0° and appropriate resetting. ~~Alternatively,~~ It is also possible to ~~deliberately~~ determine only a portion of the quadrature bias, ~~which is~~ produced by the alignment error of the two linear oscillators with respect to one another. (The expression "quadrature bias" covers both alternatives.)

The Quadrature bias is thus eliminated at its point of origin ~~itself, that is to say i.e.,~~ mechanical alignment errors of the two oscillators with respect to one another are compensated ~~for by means of~~ an electrostatic force that ~~which~~ acts on one or both oscillators and is produced by the electrostatic field.

In one ~~preferred~~ embodiment, the Coriolis gyro has first and second spring elements, with the first oscillator ~~being~~ connected by means of the first spring elements to a ~~gyro~~ frame of the Coriolis gyro and the second oscillator ~~being~~ connected by ~~means of~~ the second spring elements to the first oscillator. The electrostatic field ~~in this case~~ results in a change in the alignment of the first ~~spring elements~~ and/or a ~~change in the alignment of~~ the second spring elements. The alignment of the second spring elements is preferably varied by varying the position/alignment of

the second oscillator ~~with by means of~~ the
electrostatic field. Analogously ~~to this~~, the alignment
of the first spring elements is preferably varied by
varying the position/alignment of the first oscillator
5 by means of the electrostatic field. The change in the
positions/alignments of the oscillators in such this
case results in bending ~~of~~ the spring elements ~~which~~
~~are~~ attached to the oscillators, ~~thus~~ making it
possible to correct corresponding alignment angles of
10 the first spring elements with respect to the second
spring elements.

In a ~~one~~ particularly preferred embodiment,
the electrical field varies ~~is used to vary~~ the
alignment angles of the first and second spring
15 elements so such that they ~~the alignments of the first~~
~~and second spring elements~~ are made orthogonal with
respect to one another. ~~Once they have been made~~
~~orthogonal in this way~~, This compensates for the
quadrature-bias (component) ~~that is produced in this~~
20 ~~way~~. If there are any further contributions to ~~the~~
quadrature bias, the angle error with respect to
orthogonality is adjusted so such that the total
quadrature bias disappears. The alignment angles of the
second spring elements with respect to the first
25 oscillator are preferably varied by ~~means of~~ the
electrostatic field and the alignment angles of the
first spring elements with respect to the gyro frame of
the Coriolis gyro are unchanged. ~~not changed. However,~~

It is ~~also~~ possible to use the electrostatic field to vary only the alignment angles of the first spring elements, or to vary the alignment angles of both the first and the second spring elements.

5 The ~~method according to the invention~~ also
~~furthermore~~ provides a Coriolis gyro whose resonator is
in the form of a coupled system comprising at least one
first and one second linear oscillator. ~~and which has~~
It includes ~~has~~ a device for production of an
10 electrostatic field ~~by means of which~~ to vary the
alignment of the two oscillators with respect to one
another ~~can be varied,~~ as well as a device for
~~determination of any~~ determining quadrature bias ~~which~~
is caused by alignment errors of the two oscillators
15 with respect to one another and with other further
coupling mechanisms. ~~and~~ A control loop regulates ~~with~~
~~the control loop regulating~~ the strength of the
electrostatic field as a function of the determined
quadrature bias so ~~such~~ that the ~~determined~~ quadrature
20 bias is as small as possible.

 If the resonator comprises a first and a
second linear oscillator, then the Coriolis gyro
preferably has first and second spring elements. ~~with~~
25 The first spring elements connect ~~connecting~~ the first
oscillator to the ~~gyro~~ frame of the Coriolis gyro, and
the second spring elements connect ~~connecting~~ the
second oscillator to the first oscillator. The

alignments of the first and second spring elements are
~~in this case~~ preferably at right angles to one another
~~and The spring elements may in this case~~ be of any
desired form.

5 It has been found to be advantageous for the
second oscillator to be attached to or clamped in on
the first oscillator "at one end". "Clamped in at one
end" can ~~in this case~~ be understood not only in the
sense of the literal wording but also in a general
10 sense. In general, attached or clamped in "at one end"
means that the force is introduced from the first
oscillator to the second oscillator essentially from
one "side" of the first oscillator. If, ~~for by way of~~
example, the oscillator system were ~~to be~~ designed so
15 ~~in such a way~~ that the second oscillator were ~~is~~
bordered by the first oscillator and ~~is~~ connected to it
by means of second spring elements, then the expression
"clamped in or attached at one end" would imply that
~~the following:~~ the second oscillator is readjusted for
20 ~~the~~ movement of the first oscillator, with the first
oscillator alternately "pushing" or "pulling" the
second oscillator by means of the second spring
elements.

25 Clamping the second oscillator in at one end on
the first oscillator has the advantage that, when an
electrostatic force is exerted on the second oscillator
as a result of the alignment/position change of the

second oscillator ~~which results from this,~~ the second
spring elements can be slightly curved, thus making it
possible, without any problems, to vary the
corresponding alignment angle of the second spring
elements. If the second oscillator ~~in this example~~ were
to be attached to additional second spring elements so
~~in such a way~~ that, during movement of the first
oscillator, the second oscillator were at the same time
to be "pulled" and "pushed" by the second spring
elements, then this would be equivalent to the second
oscillator being clamped in or attached "at two ends"
to the first oscillator (with the force being
introduced to the second oscillator from two opposite
ends of the first oscillator). In such ~~this~~ case, the
additional second spring elements would produce
corresponding opposing forces when an electrostatic
field is applied, so that changes in the alignment
angles of the second spring elements could be achieved
only with difficulty. However, clamping in at two ends
is acceptable when the additional second spring
elements are designed so ~~such~~ that the influence of
these spring elements is small so that all of the
spring elements can bend without any problems. ~~in this~~
~~case as well,~~ That is, ~~to say~~ the clamping in is
effectively at one end.

Depending on the design of the oscillator,
~~structure~~ clamping in at one end can be effectively
provided just by the "influence" (force introduction)

of the additional second spring elements being 40% or less. However, this value does not present any limitation on restriction to the invention. ~~and~~ It is also feasible for the influence of the second spring elements to be more than 40%. ~~By way of~~ For example, clamping in at one end can be achieved by all of the second spring elements that ~~which~~ connect the second oscillator to the first oscillator being arranged parallel and on the same plane. ~~as one another~~ All start and end points of the second spring elements are in each case attached to the same ends of the first and second oscillator. The start and end points of the second spring elements may ~~in this case~~ each advantageously be on a common axis, with the axes intersecting the second spring elements at right angles.

If the second oscillator is attached to or clamped on the first oscillator at one end, then the first spring elements are preferably designed to ~~such that they~~ clamp the first oscillator in on the gyro frame at two ends (the expressions "at one end" and "at two ends" can be used analogously ~~here~~). As an alternative, ~~to this~~ however, it is possible for the spring elements also to be designed to ~~in such a way that they~~ clamp in the first oscillator at one end. ~~By way of~~ For example, all the first spring elements that ~~which~~ connect the first oscillator to the gyro frame of the Coriolis gyro can be arranged parallel and on the

same plane as one another, with the start and end points of the first spring elements in each case preferably being located on a common axis. It is equally possible for the spring elements to be designed ~~so in such a way~~ that the first oscillator is clamped in on the gyro frame at one end, and the second oscillator is clamped in at two ends by the first oscillator. It is also possible for both oscillators to be clamped in at two ends. For quadrature bias compensation, it has been found to be advantageous for at least one of the two oscillators to be clamped in at one end.

A further ~~advantageous~~ embodiment of a Coriolis gyro ~~according to the invention~~ has a first and a second resonator, ~~which are~~ each in the form of a coupled system comprising a first and a second linear oscillator. ~~with~~ The first resonator is being mechanically/electrostatically connected/coupled to the second resonator so such that they ~~the two resonators~~ can be caused to oscillate in antiphase with respect to one another along a common oscillation axis.

Such ~~This~~ embodiment includes ~~accordingly~~ ~~has~~ a mass system that ~~which~~ comprises two double-oscillator systems (i.e., ~~that is to say~~ two resonators) or four linear oscillators. ~~The~~ Antiphase oscillation of the two resonators with respect to one another ~~in this case~~ results in the center of gravity

of the mass system remaining unchanged (provided that the two resonators are appropriately designed). ~~This means that the~~ As a result, oscillation of the mass system cannot produce any external vibration that ~~which~~ would, in turn, result in disturbances in the form of damping/reflections. Furthermore, external vibrations and accelerations in the direction of the common oscillation axis have no influence on ~~the~~ antiphase movement of the two resonators along the common oscillation axis.

~~By way of~~ For example, the first resonator can be coupled to the second resonator via a spring system. ~~which connects the first resonator to the second resonator~~ A further option is for the first resonator to be coupled to the second resonator via an electrostatic field. Both couplings can be used alone ~~on their own~~ or in combination ~~conjunction~~. It is sufficient for the two resonators to be formed in a common substrate, so that the mechanical coupling is provided by a mechanical spring connection ~~which is~~ formed by the common substrate itself.

In this embodiment ~~as well,~~ the Coriolis gyro advantageously has a device for the production of electrostatic fields to vary ~~, by means of which~~ the alignment of the linear oscillators with respect to one another ~~can be varied,~~ a device for determination of the quadrature bias of the Coriolis gyro, and control loops

for regulating ~~by means of which~~ the strengths of the
electrostatic fields ~~so are regulated such~~ that the
determined quadrature bias is as small as possible.

5 The configurations of the first and ~~of the~~
second resonators ~~resonator~~ are preferably identical.
In this case, ~~they~~ ~~the two resonators~~ are advantageously
arranged axially symmetrically with respect to one
another ~~and with respect~~ to an axis of symmetry ~~which is~~
at right angles to the common oscillator axis (i.e. 7
10 ~~that is to say~~ the first resonator is mapped by the axis
of symmetry onto the second resonator).

~~The invention will be explained in more detail~~
~~in the following text, using an exemplary embodiment,~~
~~and with reference to the accompanying figures, in~~
15 ~~which:~~

In order to assist understanding of the
~~technical~~ background of the method of ~~according to~~ the
invention, the physical principles of a Coriolis gyro
will be explained briefly below ~~once again in the~~
20 ~~following description,~~ with reference to ~~the example of~~
a linear double-oscillator system.

The Coriolis force can be represented as:

$$\vec{F} = 2m\vec{v}_x \times \vec{\Omega}$$

\vec{F} Coriolis force

m Mass of the oscillator

\vec{v}_x Velocity of the oscillator

$\vec{\Omega}$ Rotation rate

[1]

If the mass ~~that~~ which reacts to the Coriolis force is equal to the oscillating mass, and ~~if~~ the oscillator is operated at the natural frequency ω , then:

$$2m\vec{v}_s \times \vec{\Omega} = m\vec{a}_c \quad [2]$$

The oscillator velocity is given by:

$$\vec{v}_s = \vec{v}_{s0} \sin \omega t \quad [3]$$

where

\vec{v}_{s0} = oscillator amplitude

ω = natural frequency of the oscillator

The oscillator and Coriolis accelerations are thus given by:

$$\begin{aligned} \vec{a}_s &= \vec{v}_{s0} \omega \cos \omega t \\ \vec{a}_c &= 2\vec{v}_{s0} \sin \omega t \times \vec{\Omega} \end{aligned} \quad [4]$$

The two acceleration vectors are thus spatially at right angles to one another and are offset through 90° with respect to one another in the time function (spatial and time orthogonality).

These two criteria can be employed ~~used in~~ order to separate the oscillator acceleration \vec{a}_s from

the Coriolis acceleration \tilde{a}_c . The ratio of the
abovementioned acceleration amplitudes a_c and a_s is:

$$\frac{a_c}{a_s} = \frac{2\Omega}{\omega} \quad [5]$$

5 If the rotation rate is $\Omega = 5^\circ/\text{h}$ and the
natural frequency of the oscillator is $f_s = 10 \text{ KHz}$,
then:

$$\frac{a_c}{a_s} = 7.7 \cdot 10^{-10} \quad [6]$$

For an accuracy of $5^\circ/\text{h}$, undesirable couplings
of the first oscillator to the second oscillator must
10 not exceed $7.7 \cdot 10^{-10}$, or must be constant. ~~at this~~
~~value~~ If a mass system composed of two linear
oscillators ~~is used, which are~~ coupled to one another
via spring elements is employed, then the accuracy of
the spatial orthogonality between the oscillation mode
15 and the measurement mode is limited due to ~~because of~~
the alignment error of the spring elements. ~~The~~
Achievable accuracy (limited by manufacturing
tolerances) is 10^{-3} to 10^{-4} . ~~The accuracy of the Time~~
orthogonality accuracy is limited by the phase accuracy
20 of the electronics at, for example, 10 KHz , which can
likewise be complied with only to at most 10^{-3} to 10^{-4} .
This means that the ratio of the accelerations as
defined above cannot be satisfied.

Realistically, the resultant error in the

measured acceleration ratio a_c/a_s is:

$$\frac{a_c}{a_s} = 10^{-6} \text{ to } 10^{-8} \quad [7]$$

The spatial error results in a so-called quadrature bias B_Q , which, together with the time phase error Δ_ϕ , results in a bias B:

$$B_Q = 6.5 \cdot 10^6 \text{ }^\circ/\text{h to } 6.5 \cdot 10^5 \text{ }^\circ/\text{h}$$

$$\Delta_\phi = 10^{-3} \text{ to } 10^{-4}$$

$$B = B_Q \cdot \Delta_\phi = 6,500 \text{ }^\circ/\text{h to } 65 \text{ }^\circ/\text{h} \quad [8]$$

The quadrature bias thus results in a major limitation ~~restriction to the~~ measurement accuracy. In this case, it should be noted that the preceding ~~above~~ error analysis takes account only of the direct coupling of the oscillation mode to the read mode. Further quadrature bias components also exist and occur, for example, as a result of couplings with other oscillation modes.

Figure 1 illustrates ~~shows~~ the schematic design of a linear double oscillator 1 with corresponding electrodes including ~~as well as~~ a block diagram of associated evaluation/excitation electronics 2. The linear double oscillator 1 is preferably produced by ~~means of etching processes from~~ a silicon wafer. ~~and~~ It has a first linear oscillator 3, a second linear oscillator 4, first spring elements 5_1 to 5_4 , second spring elements 6_1 and 6_2 as well as parts of an

intermediate frame 7_1 and 7_2 and of a gyro frame 7_3 and 7_4 . The second oscillator 4 is mounted within the first oscillator 3 ~~to such that it can~~ oscillate, and is connected to it via the second spring elements 6_1 , 6_2 .

5 The first oscillator 3 is connected to the gyro frame 7_3 , 7_4 by ~~means of~~ the first spring elements 5_1 to 5_4 and the intermediate frame 7_1 , 7_2 .

10 ~~Furthermore,~~ First excitation electrodes 8_1 to 8_4 , first read electrodes 9_1 to 9_4 , second excitation electrodes 10_1 to 10_4 , and second read electrodes 11_1 and 11_2 are also provided. All of the electrodes are mechanically connected to the gyro frame, although but ~~are~~ electrically isolated. (The expression "gyro frame" refers to means a mechanical, non-oscillating structure in which the oscillators are "embedded", e.g., for ~~example~~ the non-oscillating part of the silicon wafer).

20 When ~~if~~ the first oscillator 3 is excited by ~~means of~~ the first excitation electrodes 8_1 to 8_4 to oscillate in the X_1 direction, such ~~then this~~ movement is transmitted through the second spring elements 6_1 , 6_2 to the second oscillator 4 (alternate "pulling" and "pushing"). The vertical alignment of the first spring elements 5_1 to 5_4 prevents the first oscillator 3 from moving in the X_2 direction. However, ~~a~~ vertical
25 oscillation can be carried out by the second oscillator 4 as a result of the horizontal alignment of the second spring elements 6_1 , 6_2 . When corresponding Coriolis

forces ~~accordingly~~ occur, then the second oscillator 4 is excited to oscillate in the X2 direction.

A read signal ~~that which~~ is read from the first read electrodes 9₁ to 9₄ and ~~is~~ proportional to the amplitude/frequency of the X1 movement of the first oscillator 3 is supplied, via appropriate amplifier elements 21, 22 and 23, to an analog/digital converter 24. An appropriately digitized output signal from the analog/digital converter 24 is demodulated ~~not only~~ by a first demodulator 25 ~~and but also~~ by a second demodulator 26 to form corresponding output signals, with the two demodulators operating with an offset of 90° with respect to one another. The output signal from the first demodulator 25 whose output signal controls a frequency generator 30 ~~so such~~ that the signal occurring ~~which occurs~~ downstream from the demodulator 25 is regulated at zero is supplied to a first regulator 27 ~~in order~~ to regulate the frequency of the excitation oscillation (the oscillation of the mass system 1 in the X1 direction). Analogously ~~to this~~, the output signal from the second demodulator 26 is regulated at a constant value ~~which is~~ (predetermined by the electronics component 29). A second regulator 31 insures ~~ensures~~ that the amplitude of the excitation oscillation is regulated. The output signals from the frequency generator 30 and ~~from~~ the amplitude regulator 31 are multiplied by one another ~~at by means of~~ a multiplier 32. An output signal from the multiplier 32, which is

proportional to the force to be applied to the first excitation electrodes 8_1 to 8_4 , acts not only on a first force/voltage converter 33 but also on a second force/voltage converter 34, which use the digital force signal to produce digital voltage signals. The digital output signals from the force/voltage converters 33, 34 are converted by ~~via a~~ first and ~~a~~ second digital/analog converters ~~converter~~ 35, 36 to corresponding analog voltage signals. ~~which are~~ Such signals are then passed to the first excitation electrodes 8_1 to 8_4 . The first ~~regulator 27~~ and the second regulators ~~regulator~~ 27, 31 readjust the natural frequency of the first oscillator 3 and set the amplitude of the excitation oscillation to a specific, predeterminable value.

When Coriolis forces occur, resultant ~~the~~ movement of the second oscillator 4 in the X2 direction (read oscillation) ~~that results from this~~ is detected by the second read electrodes 11_1 , 11_2 , and a read signal, ~~which is~~ proportional to the movement of the read oscillation, is supplied via appropriate amplifier elements 40, 41 and 42 to an analog/digital converter 43 (see Figure 2). A digital output signal from the analog/digital converter 43 is demodulated by a third demodulator 44 in phase with the direct-bias signal and ~~is~~ demodulated by a fourth demodulator 45, offset through 90° . A corresponding output signal from the first demodulator 44 is applied to a third regulator 46, whose output signal is a compensation signal that ~~and~~

corresponds to the rotation rate Ω to be measured. An output signal from the fourth demodulator 45 is applied to a fourth regulator 47 whose output signal is a compensation signal ~~and is~~ proportional to the quadrature bias to be compensated. ~~for~~ The output signal from the third regulator is modulated by ~~means of~~ a first modulator 48, and the output signal from the fourth regulator 47 is modulated in an analogous manner ~~to this by means of~~ a second modulator 49, so that amplitude-regulated signals are produced whose frequencies correspond to the natural frequency of the oscillation in the X1 direction ($\sin \approx 0^\circ$, $\cos \approx 90^\circ$). Corresponding output signals from the modulators 48, 49 are added in an addition stage 50, whose output signal is supplied both to a third force/voltage converter 51 and to a fourth force/voltage converter 52. The corresponding output signals for the force/voltage converters 51, 52 are supplied to digital/analog converters 53, 54, whose analog output signals are applied to the second excitation electrodes 10_2 to 10_3 , and reset the oscillation amplitudes of the second oscillator 4.

The electrostatic field ~~which is~~ produced by the second excitation electrodes 10_1 and 10_4 (or the two electrostatic fields ~~which are~~ produced by the electrode pairs $10_1, 10_3$ and $10_2, 10_4$) results in an alignment/position change of the second oscillator 4 in the X2 direction, and thus in a change in the alignments

of the second spring elements 6_1 to 6_2 . The fourth regulator 47 regulates the signal ~~which is~~ applied to the second excitation electrodes 10_1 and 10_4 , so in such a way that the quadrature bias ~~which is~~ included in the compensation signal of the fourth regulator 47 is as small as possible, or disappears. A fifth regulator 55, a fifth and a sixth force/voltage converter 56, 57 and two analog/digital converters 58, 59 are used for this purpose.

The output signal from the fourth regulator 47, which is a measure of the quadrature bias, is supplied to the fifth regulator 55, that ~~which~~ regulates the electrostatic field ~~that is~~ produced by the two excitation electrodes 10_1 and 10_4 , so that in such a way ~~that~~ the quadrature bias B_0 disappears. ~~For this purpose,~~ An output signal from the fifth regulator 55 is ~~in each case~~ supplied to the fifth and sixth force/voltage converters 56, 57, employing ~~which use~~ the digital force/output signal from the fifth regulator 55 to produce digital voltage signals that ~~These~~ are then converted to analog voltage signals in the analog/digital converters 58, 59. The analog output signal from the analog/digital converter 58 is supplied to the second excitation electrode 10_1 , ~~or~~ (alternatively to electrode 11_1). The analog output signal from the analog/digital converter 59 is supplied to the second excitation electrode 10_4 , ~~or~~ (alternatively to electrode 11_2).

5 ~~As Since~~ the second oscillator 4 is clamped in
only by the second spring elements 6_1 to 6_2 (~~clamping~~
~~clamped in~~ at one end), such the alignment of the these
spring elements can be varied without problem by the
electrostatic field ~~any problems~~. It is additionally
~~also~~ possible to provide additional second spring
elements, ~~which result~~ resulting in the second
oscillator 4 being clamped in at two ends, provided that
such these additional spring elements are appropriately
10 designed to insure ~~ensure~~ that clamping in at one end is
effective. ~~effectively achieved~~. In order to permit
~~allow~~ the same effect for the spring elements 5_1 , 5_2 (and
for the spring elements 5_3 , 5_4 as well) the third and
fourth spring elements 5_3 , 5_4 , as well as ~~and~~ the first
15 and second spring elements 5_1 , 5_2 may be omitted, ~~thus~~
resulting in the first oscillator 3 being clamped in at
one end (together with an appropriately modified
electrode configuration, ~~which is~~ not shown here). In
such a situation ~~such as this~~, the second oscillator 4
20 ~~could~~ may also be attached to the first oscillator by
~~means of~~ further spring elements ~~in order~~ to achieve
clamping in at two ends.

25 The electrode arrangements ~~which are~~ shown
in Figures 1 and 2 may be varied. For example, the
electrodes ~~which are~~ identified by the reference numbers
 8_1 , 9_1 , 9_2 , 8_2 as well as 8_3 , 9_3 , 9_4 , 8_4 in Figures 1 and 2
may alternatively ~~in each case~~ be combined to form one

electrode. An electrode ~~which has been~~ combined in this way may be allocated a plurality of tasks by using the use of suitable carrier frequency methods (i.e., that is to say the electrode has a read, excitation and compensation functions function at the same time). The electrodes ~~which are~~ identified by the reference numbers 11₁, 10₁, 10₃ as well as 11₂, 10₂ and 10₄ can also ~~alternatively~~ be combined to form ~~in each case~~ one electrode.

~~One further possible embodiment of the Coriolis gyro according to the invention and its method of operation will be described in more detail in the following description with reference to Figure 3.~~

~~A~~ ~~One~~ preferred embodiment of the Coriolis gyro of according to the invention as well as and its method of operation will be described in more detail in the following description with reference to Figure 3, a schematic illustration of a mass system comprising four linear oscillators with corresponding measurement and control loops for rotation rate and quadrature mass, as well as auxiliary control loops for compensation of the quadrature bias. Figure 3 shows The schematic layout of coupled system 1' comprises comprising a first resonator 70₁ and a second resonator 70₂. The first resonator 70₁ is coupled to the second resonator 70₂ by via a mechanical coupling element (a spring) 71. The first and the second resonator 70₁, 70₂ are formed in a common

substrate and ~~may~~ can be caused to oscillate in antiphase with respect to one another along a common oscillation axis 72. The first and ~~the~~ second resonators ~~resonator~~ 70_1 , 70_2 are identical, and are mapped onto one another via an axis of symmetry 73. The design of the first and ~~of the~~ second resonator 70_1 , 70_2 has ~~already~~ been explained in conjunction with Figures 1 and 2 and will therefore not be explained again. (Identical and mutually corresponding components or component groups are identified by the same reference numbers with identical components which are associated with different resonators being identified by different indices.)

A ~~One~~ major difference between the double oscillators shown in Figure 3 and those ~~the double~~ ~~oscillators~~ shown in Figures 1 and 2 is that some of the individual electrodes are physically combined to form one overall electrode. For example, the individual electrodes ~~which are~~ identified by the reference numbers 8_1 , 8_2 , 9_1 and 9_2 in Figure 3 ~~thus~~ form a common electrode. ~~Further, Furthermore,~~ the individual electrodes ~~which are~~ identified by the reference numbers 8_3 , 8_4 , 9_3 and 9_4 form a common electrode, ~~and~~ those with the reference numbers 10_4 , 10_2 , 11_2 as well as the reference numbers 11_1 , 10_3 and 10_1 each form an overall electrode. The same applies in an analogous manner to the other double-oscillator system.

During operation of the coupled system 1' in

accordance with ~~according to~~ the invention, the two resonators 70_1 , 70_2 oscillate in antiphase along the common oscillation axis 72. The coupled system 1' is thus not susceptible to external disturbances or to
5 ~~those disturbances which are~~ emitted by the coupled system 1' itself into the substrate in which the resonators 70_1 and 70_2 are mounted.

When the coupled system 1' is rotated, ~~then~~ the second oscillators 4_1 and 4_2 are deflected in
10 mutually opposite directions (i.e., ~~in~~ the X2 direction and ~~in the~~ opposite direction to the X2 direction). When an acceleration of the coupled system 1' occurs, ~~then~~ the second oscillators 4_1 , 4_2 are each deflected in the same direction, i.e., ~~specifically~~ in the same direction
15 as the acceleration provided that such ~~this~~ acceleration is in the X2 direction, or in the opposite direction. ~~to it~~ Accelerations and rotations can thus be measured simultaneously or selectively. Quadrature bias compensation can be carried out ~~at the same time~~ during
20 the measurement process in the resonators 70_1 , 70_2 . However, this is not absolutely essential.

In principle, it is possible to operate the coupled system 1' on the basis of the evaluation/excitation electronics 2 described with
25 reference to ~~in~~ Figures 1 and 2. ~~However,~~ An alternative method (carrier frequency method) is ~~used~~ instead used ~~of this~~ in the embodiment of ~~shown in~~ Figure 3. Such

This operating method will be described below. ~~in the following text.~~

The evaluation/excitation electronics 2 ~~which are~~ identified by the reference number 2' include have three control loops: a first control loop for excitation and/or control of an antiphase oscillation of the first oscillators 3_1 and 3_2 along the common oscillation axis 72, a second control loop for resetting and compensation of the oscillations of the second oscillator 4_1 along the X2 direction, and a control loop for resetting and compensation of the oscillations of the second oscillator 4_2 along the X2 direction. The three described control loops include have an amplifier 60, an analog/digital converter 61, a signal separation module 62, a first to third demodulation module 63_1 to 63_3 , a control module 64, an electrode voltage calculation module 65, a carrier frequency addition module 67, and a first to sixth digital/analog converter 66_1 to 66_6 .

Carrier frequencies can be applied to the electrodes 8_1 to 8_8 , 9_1 to 9_8 , 10_1 to 10_8 and 11_1 to 11_4 for tapping excitation of the antiphase oscillation or of the oscillations of the second oscillators 4_1 , 4_2 . This may be accomplished in a number of ways. They include : a) using three different frequencies, with one frequency ~~being~~ associated with each control loop, b) using square-wave signals with a time-division multiplexing method, and or c) using random phase

scrambling (stochastic modulation method).

The carrier frequencies are applied to the electrodes 8_1 to 8_8 , 9_1 to 9_8 , 10_1 to 10_8 and 11_1 to 11_4 via the associated signals $UyAo$, $UyAu$ (for the second oscillator 4_1), ~~and~~ Uxl , Uxr (for the antiphase resonance of the first oscillators 3_1 to 3_2) and as well as ~~as~~ $UyBu$ and $UyBo$ (for the second oscillator 4_2) that ~~which~~ are produced in the carrier frequency addition module 67 and ~~are~~ excited in antiphase with respect to the abovementioned frequency signals. The oscillations of the first and second oscillators 3_1 , 3_2 , 4_1 and 4_2 are tapped off via those parts of the gyro frame ~~which are~~ identified by the reference numbers 7_7 , 7_9 , 7_{11} and 7_{13} , ~~and in this case are additionally~~ (used as tapping electrodes in addition to their function as suspension points for the mass system). For this ~~purpose~~, the two resonators 70_1 , 70_2 are preferably ~~and advantageously~~ designed to be electrically conductive, with all of the frames, springs and connections. The signal, ~~which is~~ tapped off by means of the gyro frame parts 7_7 , 7_9 , 7_{11} and 7_{13} and ~~is~~ supplied to the amplifier 60, contains information about all three oscillation modes. It ~~and~~ is converted by the analog/digital converter 61 to a digital signal ~~which is~~ supplied to the signal separation module 62.

The assembled signal is separated into three different signals in the signal separation module 62: x

(which contains information about the antiphase oscillation), yA (which contains information about the deflection of the second oscillator 4₁) ~~and as well as~~ yB (which contains information about the deflection of the second oscillator 4₂). The signals are separated differently in accordance with ~~depending on~~ the type of carrier frequency method used (see a) to c) above). ~~and~~ Separation is carried out by demodulation with the corresponding signals of the carrier frequency method ~~that is used~~. The signals x, yA and yB are supplied to the demodulation modules 63₁ to 63₃, that ~~which~~ demodulate them with ~~using~~ an operating frequency of the antiphase oscillation for 0° and 90°. The control module 64 and ~~as well as~~ the electrode voltage calculation module 65 for regulation/calculation of the signals Fx1/r or Ux1/r, respectively, are preferably configured analogously to the electronics module 2 of ~~shown in~~ Figure 1. The control module 64 and the electrode voltage calculation module 65 (for regulation/calculation of the signals FyAo/u, UyAo/u, and FyBo/u, UyBo/u) are preferably designed analogously to the electronics module 2 of ~~shown in~~ Figure 2. The only difference is that the signals for ~~the~~ resetting ~~of~~ the rotation rate and ~~of~~ the quadrature after the multiplication by the operating frequency are passed together with DC voltages for the quadrature auxiliary regulator to a combined electrode pair. The two signals are therefore added, so that ~~the~~ calculation of the electrode voltages includes the resetting signals for ~~the~~ oscillation frequency and the

DC signal for ~~the~~ quadrature regulation as well as ~~the~~ frequency tuning. The electrode voltages $U_{x1/r}$, $U_{yA0/u}$ and $U_{yB0/u}$ calculated in this way are then added to the carrier-frequency signals and ~~are~~ passed jointly via the analog/digital converters 66₁ to 66₆ to the electrodes.

Figure 4 is a block diagram of an embodiment of a control system for incorporation into a mass system in accordance with Figure 3. It shows one preferred embodiment of the control system ~~that is~~ identified by the reference number 64 in Figure 3. The control system 64 includes ~~has~~ a first to third part 64₁ to 64₃. The first part 64₁ has a first regulator 80, a frequency generator 81, a second regulator 82, an electronics component 83, an addition stage 84 and a multiplier 85. The ~~method of~~ operation of the first part corresponds essentially to that ~~the method of operation~~ of the electronics module 2 of shown in Figure 1 and will therefore not be described once again ~~here~~. The second part 64₂ has a first regulator 90, a first modulator 91, a second regulator 92, a second modulator 93 and a third regulator 94. A first and a second addition stage 95, 96 are also provided. A rotation rate signal Ω can be determined at the output of the first regulator 90, and an assembled signal comprising the compensation of the ~~a~~ quadrature bias B_0 and an acceleration A can be determined at the output of the third regulator 94.

The third part 64₃ of the control system 64

has a first regulator 100, a first modulator 101, a second regulator 102, a second modulator 103 and a third regulator 104. A first and a second addition stage 105, 106 are also provided. A rotation rate signal Ω with a negative mathematical sign can be tapped off at the output of the first regulator 100 and an assembled signal comprising the compensation of the quadrature bias B_0 with a negative mathematical sign and an acceleration signal A can be tapped off at the output of the third regulator 104. The method of operation of the second and of the third ~~parts~~ ~~part~~ 64₂ and 64₃ corresponds to that of the electronics module 2 illustrated in Figure 2, and will therefore not be explained ~~once~~ again ~~here~~.

Only the signals for resetting ~~of the~~ rotation rate and ~~the~~ quadrature, after ~~the~~ multiplication by the operating frequency, are passed, together with the DC voltages for the quadrature auxiliary regulator, to a combined electrode pair. The two signals are therefore added so that the calculation of the electrode voltages includes the reset signals for ~~the~~ oscillation frequency and the DC signal for quadrature regulation. The electrode voltages $U_{x1/r}$, $U_{yA0/u}$ and $U_{yB0/u}$ thusly calculated ~~in this way~~ are then added to the carrier frequency signals and ~~are~~ jointly passed via the analog/digital converters 66₁ to 66₆ to the electrodes.

The carrier frequency methods described above

with antiphase excitation have the advantage that a signal is applied to the amplifier 60 only when the linear oscillators 3_1 , 3_2 , as well as 4_1 and 4_2 , are deflected. The frequency signals ~~which are~~ used for excitation may be discrete frequencies or square-wave signals. Square-wave excitation is preferred, as it is easier to produce and process.

Linear double oscillators are distinguished by particularly high quality due ~~owing to the~~ linear movement on the wafer plane. ~~The~~ Compensation for the quadrature bias in ~~the case of~~ linear resonators in which at least one oscillator is clamped in at one end can be achieved, according to the invention, globally by adjustment of the orthogonality of the springs. This is achieved by varying the angle of the springs of the oscillator, ~~which is~~ clamped in at one end, by means of a DC voltage, such that the measured quadrature bias B_0 becomes zero. As described above, a corresponding control loop is used for this purpose to regulate ~~which regulates~~ the abovementioned DC voltage so ~~such~~ that $B_0 = 0$. ~~The This~~ control loop compensates for the quadrature bias at the point of origin and improves the accuracy of linear oscillation gyros by a number of orders of magnitude.

The linear oscillators of a resonator are preferably each operated at double resonance.

While the invention has been described with reference to a presently-preferred embodiment, it is not limited thereto. Rather, this invention is limited only insofar as it is defined by the following set of patent claims and includes within its scope all equivalents thereof.

5

What is claimed is:

~~Patent Claims~~

1 1. A method for quadrature-bias compensation in a
2 Coriolis gyro, whose resonator (1) is in the form of a
3 coupled system comprising a first and a second linear
4 oscillator (3, 4), having the following steps:
5 - determination of the quadrature bias of the
6 Coriolis gyro,
7 - production of an electrostatic field in order to
8 vary the mutual alignment of the two oscillators (3, 4)
9 with respect to one another, with the alignment/strength
10 of the electrostatic field being regulated such that the
11 determined quadrature bias is as small as possible.

1 2. The method as claimed in claim 1, characterized in
2 that the electrostatic field results in a change in the
3 alignment of first spring elements (5_1 to 5_4), which
4 connect the first oscillator (3) to a gyro frame (7_3 , 7_4)
5 of the Coriolis gyro, and/or a change in the alignment
6 of second spring elements (6_1 , 6_2), which couple the
7 first oscillator (3) to the second oscillator (4).

3. The method as claimed in claim 2, characterized in that the alignment of the first spring elements (5_1 to 5_4) is varied by varying the position/alignment of the first oscillator (3) by means of the electrostatic field, and in that the alignment of the second spring elements (6_1 , 6_2) is varied by varying the position/alignment of the second oscillator (4) by means of the electrostatic field.

4. The method as claimed in claim 2 or 3, characterized in that the electrical field results in the alignments of the first and second spring elements (6_1 , 6_2 , 5_1 to 5_4) being made orthogonal with respect to one another.

5. The method as claimed in one of claims 2 to 4, characterized in that the second oscillator (4) is attached to/clamped in on the first oscillator (3) at one end by means of the second spring elements (6_1 , 6_2), and/or the first oscillator (3) is attached to/clamped in on a gyro frame of the Coriolis gyro at one end by means of the first spring elements (5_1 to 5_4),

1 6. A Coriolis gyro, whose resonator (1) is in the form
2 of a coupled system comprising a first and a second
3 linear oscillator (3, 4),
4 characterized by

5 - a device for production of an electrostatic field
6 ($11_1'$, $11_2'$, 10_1 to 10_4) by means of which the alignment
7 of the two oscillators (3, 4) with respect to one
8 another can be varied,

9 - a device (45, 47) for determination of any
10 quadrature bias of the Coriolis gyro, and

11 - a control loop (55, 56, 57), by means of which the
12 strength of the electrostatic field is regulated as a
13 function of the determined quadrature bias such that the
14 determined quadrature bias is as small as possible.

1 7. The Coriolis gyro as claimed in claim 6,
2 characterized in that the first oscillator (3) is
3 connected by means of first spring elements (5_1 to 5_4) to
4 a gyro frame (7_1 , 7_2) of the Coriolis gyro, and the
5 second oscillator (4) is connected by means of second
6 spring elements (6_1 , 6_2) to the first oscillator (3).

8. The Coriolis gyro as claimed in claim 7,
characterized in that the first and second spring
elements are arranged/designed such that the alignment
angle of the first spring elements (5_1 to 5_4) with
respect to the gyro frame (7_3 , 7_4) can be varied by means
of the electrostatic field, and/or in that the alignment
angle of the second spring elements (6_1 , 6_2) with respect
to the first oscillator (3) can be varied by means of
the electrostatic field.

9. The Coriolis gyro as claimed in claim 7 or 8,
characterized in that the second oscillator (4) is
attached to/clamped in on the first oscillator (3) at
one end by means of the second spring elements (6_1 , 6_2),
and/or the first oscillator (3) is attached to/clamped
in on a gyro frame of the Coriolis gyro at one end by
means of the first spring elements (5_1 to 5_4).

10. The Coriolis gyro as claimed in one of claims 7 to
9, characterized in that all of the second spring
elements (6_1 to 6_2) which connect the second oscillator
(4) to the first oscillator (3) are designed such that
force is introduced from the first oscillator (3) to the
second oscillator (4) essentially from one side of the
first oscillator (3).

1 11. The Coriolis gyro as claimed in one of claims 7 to
2 10, characterized in that all of the first spring
3 elements (5₁ to 5₄) which connect the first oscillator
4 (3) to the gyro frame (7₃, 7₄) of the Coriolis gyro are
5 arranged parallel and on the same plane as one another,
6 with the start and end points of the first spring
7 elements (5₁ to 5₄) each being located on a common axis.

1 12. A Coriolis gyro (1'), having a first and a second
2 resonator (70₁, 70₂), which are each in the form of a
3 coupled system comprising a first and a second linear
4 oscillator (3₁, 3₂, 4₁, 4₂), with the first resonator
5 (70₁) being mechanically/electrostatically
6 connected/coupled to the second resonator (70₂) such
7 that the two resonators can be caused to oscillate in
8 antiphase with respect to one another along a common
9 oscillation axis (72).

1 13. The Coriolis gyro (1') as claimed in claim 12,
2 characterized by:

- 3 - a device for production of electrostatic fields
4 (11₁, 11₂, 10₁ to 10₄, and 11₃, 11₄, 10₅ to 10₈), by means
5 of which the alignment of the linear oscillators (3₁, 3₂,
6 4₁, 4₂) with respect to one another can be varied,
- 7 - a device for determination of the quadrature bias
8 of the Coriolis gyro (1'), and
- 9 - control loops (64), by means of which the strengths
10 of the electrostatic fields are regulated such that the
11 determined quadrature bias is as small as possible.

1 14. The Coriolis gyro (1') as claimed in claim 12 or
 2 13, characterized in that the configurations of the
 3 first and of the second resonator (70_1 , 70_2) are
 4 identical, with the resonators (70_1 , 70_2) being arranged
 5 axially symmetrically with respect to one another, with
 6 respect to an axis of symmetry (73) which is at right
 7 angles to the common oscillation axis (72).

1 15. The Coriolis gyro (1') as claimed in one of claims
 2 12 to 14, characterized in that the first oscillators
 3 (3_1 , 3_2) are each connected by means of first spring
 4 elements ($5_1 - 5_8$) to a gyro frame ($7_1 - 7_{14}$) of the
 5 Coriolis gyro, and the second oscillators (4_1 , 4_2) are
 6 each connected by means of second spring elements
 7 ($6_1 - 6_4$) to one of the first oscillators (3_1 , 3_2).

ABSTRACT

~~Method for quadrature bias compensation in a Coriolis gyro, as well as a Coriolis gyro which is suitable for this purpose~~

In A method for quadrature-bias compensation in a Coriolis gyro, whose resonator (1) is in the form of a coupled system comprising a first and a second linear oscillator. (3, 4), The quadrature bias of the Coriolis gyro is determined. An electrostatic field is produced by variation of the mutual alignment of the two oscillators (3, 4) with respect to one another. with The alignment/strength of the electrostatic field is ~~being~~ regulated so such that the determined quadrature bias is made as small as possible.

~~(Figure 2)~~

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